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Effect of Plating of Carbon Fibres with Ni on Properties of Fe-Based Materials

Mahmud Elkady[1], A. V. Minitsky[1], I. Yu. Trosnikova[1], P. I. Loboda[1], and D. S. Leonov[2]

[1]*National Technical University of Ukraine*
'Igor Sikorsky Kyiv Polytechnic Institute',
37, Peremogy Ave.,
UA-03056 Kyiv, Ukraine
[2]*Technical Centre, N.A.S. of Ukraine,*
13, Pokrovs'ka Str.,
UA-04070 Kyiv, Ukraine

The structure and properties of the material based on carbonyl iron reinforced with carbon fibres, which are previously plated with nickel, are studied. Uncoated carbon fibres are used for the first group of samples, and nickel-plated carbon fibres are used for the second group. Nickel plating is found to provide better adhesive interaction between carbon fibres and iron. As shown, the reinforcement with nickel-plated carbon fibres allows increasing both the strength limit and the plasticity of materials. At the same time, for samples sintered at 900°C, the strength does not increase fundamentally (from 661 MPa to 697 MPa), but the relative elongation doubles from 22.7% to 45.1%. Using the method of fractographic analysis, the viscous nature of the destruction of the samples is established, and it is shown that the microrelief of the surface is characterized by oblique fractures, which is due to the formation of viscous dimples under the action of tangential stresses. An increase in the sintering temperature to 1000°C provides an increase in the compressive strength of the samples to 1002–1185 MPa, while the samples containing clad fibres have strength of 180–185 MPa higher than the strength of samples with carbon fibres not plated with nickel.

У роботі досліджено формування структури та властивості матеріялу на основі карбонільного заліза, армованого вуглецевими волокнами, попередньо плакованими ніклем. Для першої партії зразків було застосовано неплаковані вуглецеві волокна, а для другої — вуглецеві волокна, плаковані ніклем. Встановлено, що плакування ніклем забезпечує кращу адгезійну взаємодію між вуглецевими волокнами та залізом. Показано, що армування вуглецевими волокнами, плакованими ніклем, уможливлює збільшити як границю міцности, так і пластичність матеріялів. Для зразків, спечених за 900°C, міцність зростає непринципово — від 661 МПа до 697 МПа, однак відносне видовження збільшується вдвічі — від 22,7% до 45,1%. Методом фрактографічної аналізи встановлено в'язкий характер руйнування зразків і показано, що мікрорельєф поверхні характеризується косими зламами, що зумовлено утворенням в'язких ямок під дією дотичних напружень. Збільшення температури спікання до 1000°C забезпечує зростання міцности на стиснення зразків до 1002–1185 МПа; зразки, які містять плаковані волокна, мають міцність, на 180–185 МПа вищу за міцність зразків з вуглецевими волокнами, неплакованими ніклем.

Key words: iron, nickel, plating, reinforcement, carbon fibres.

Ключові слова: залізо, нікель, плакування, армування, вуглецеві волокна.

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1. INTRODUCTION

Alloying of iron aimed at obtaining steels with special properties is the process of adding other metallic and non-metallic elements to iron to produce alloys with heightened quality. There are alloying elements, which increase corrosion resistance, malleability, and elastic moduli of steels. Sheets and profiles of alloyed steels are widely used to produce various structures in mechanical engineering and construction. The properties of certain steel have to meet the service conditions of the products made from this steel and the technologies used for connecting individual parts [1].

Thermal fatigue and wear are one of the main causes of failure of parts, which limits their service lifecycle. Therefore, it is important to prolong the service lifecycle of parts by strengthening the material both in volume and on surface. The addition of reinforcing carbon fibres, which have high elastic modulus and strength, is one of the techniques for strengthening steel products [2]. Moreover, the addition of discrete fibres uniformly distributed in the steel matrix provides isotropy of the material properties and, at the same time, it increases its strength.

The properties of iron can be improved with various alloying elements: taking into account the thermodynamic properties of metals, we can assume that the production of an iron–nickel alloy is free from any complications, but in practice, some problems appear [3]. Due to the side oxidation process, iron changes from the divalent state to the trivalent one during the interaction of the metals upon the production of an iron–nickel alloy. As a result, the yield of the alloy decreases, and some physical properties deteriorate. Well-known developers and suppliers of iron powders and Fe-based alloys widely use special iron powders coated with organic components in their latest developments [4–6].

Recently, amorphous alloys have been used with aim to solve this problem due to their unique physical, mechanical, and chemical properties [7]. In most cases, amorphous alloys are produced in the form of ribbons, powders, or wire with small thickness or diameter; so, their use as structural materials is limited [8]. The coatings have always been used for strengthening the surface of cast iron, so it was possible to achieve high hardness. Nickel is beneficial as it prevents the diffusion of carbon and reduces the cooling tendency of the structure in the molten partially zone. Therefore, Fe–Ni-based alloys have always been used as fillers in the processes of welding cast iron with spherical carbides. However, the mechanical properties of Fe–Ni-based alloys are always poor, when they are used in the processing of high-strength cast irons [9].

Thus, the purpose of this work was to study the structural, physical, and mechanical properties of materials based on carbonyl iron reinforced with carbon fibres additionally coated with nickel.

2. EXPERIMENTAL TECHNIQUES AND RESULTS

The samples for the study were produced in accordance with the following technological process.

First, mixtures with certain compositions were prepared (Table 1).

Carbon fibres were previously coated with Ni by chemical deposition (reducing nickel chloride with hypophosphite in an aqueous solution). This method is relatively inexpensive and does not require special expensive equipment, while it allows obtaining high-quality coatings from various materials with high adhesion between the substrate and the coating [10].

However, despite the advantages of chemical deposition technique, there are no systematic data and clear recipes for plating carbon fibres with metal coatings, so this question is to be studied. The process of nickel deposition by chemical reducing its salts with

TABLE 1. Initial compositions of mixtures (wt.%).

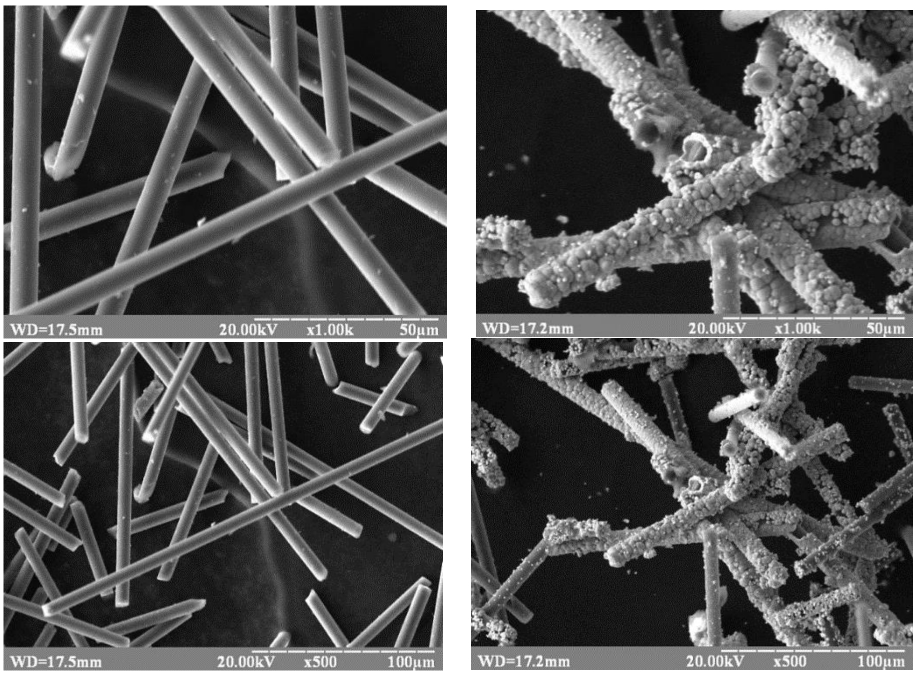
Mixture	Ratio of components, wt.%			
	Carbonyl iron	Carbon fibres coated with Ni	Carbon fibres	Phenolic binder
1	97	0.5	—	2.5
2	97	—	0.5	2.5

hypophosphite solution provides the possibility to produce a coating with uniform thickness and quality on all the fibre surfaces, which contact with the solution. Nickel was deposited on carbon fibres as follows. Carbon fibres were placed into a bath with a working solution containing nickel chloride (as a source of nickel), sodium citric acid, sodium hypophosphite, and ammonium chloride (complexing agents). To adjust the pH level of the solution, a 25% ammonia solution was added to the bath that provided a stable alkaline environment. The alkaline solution has high stability, its composition is easy to adjust, it has no tendency to self-discharge, and it is good for long-term operation. The process of reduction in the alkaline solution occurs by the following reaction:

$$Ni^{2} + 2H_2PO_2 + 4OH \rightarrow Ni + 2H_2PO_3^{2-} + H_2 + 2H_2O.$$

The optimal parameters, *i.e.*, temperature of 82–88°C and pH $\geq$ 11, were determined; rate of nickel deposition on carbon fibres was 2–3 μm/h. The carbon fibres before and after plating are shown in Fig. 1.

The next stage was dipping of carbon fibres into the iron mix-



a *b*

Fig. 1. Carbon fibres: *a*—non-plated carbon fibres; *b*—Ni-plated carbon fibres.

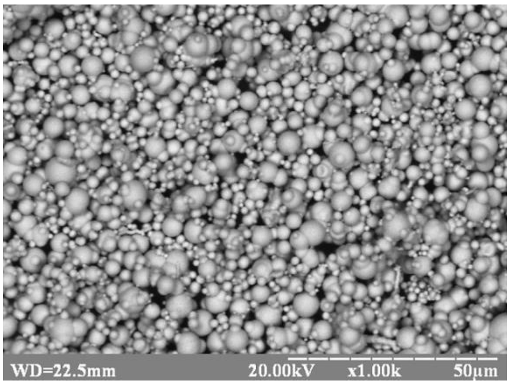


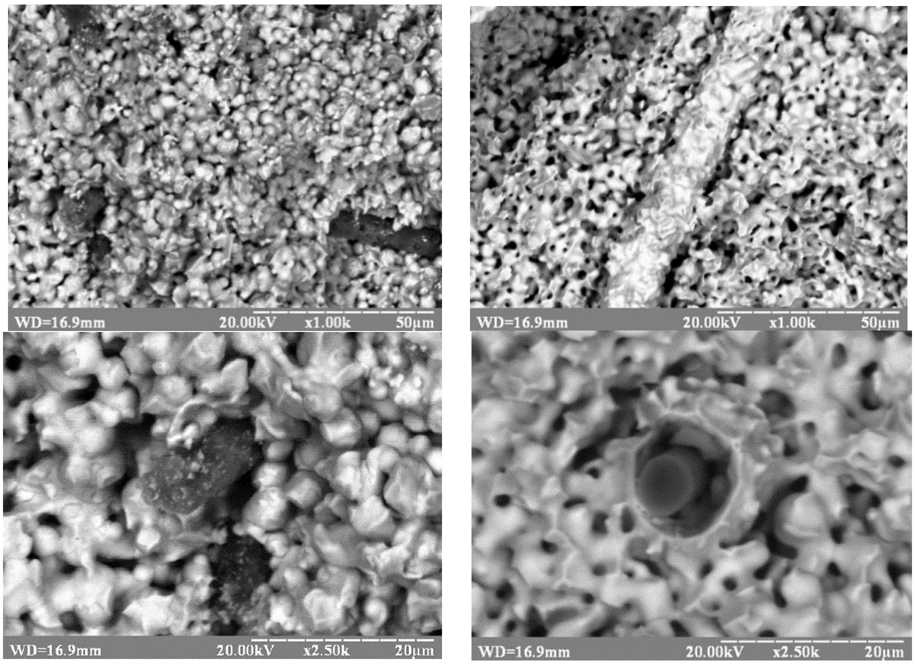
Fig. 2. Carbonyl iron powder.

ture. Carbonyl iron powders had a spherical shape and a size of 2–5 μm (Fig. 2). The small size of the carbonyl iron particles provides higher sintering activity due to the high specific surface area, which allows using lower sintering temperatures for the Fe-based materials.

The next stage was mixing iron powder and carbon fibres with the phenolic binder. The samples were pressed in a hydraulic press under a pressure of 350 MPa. Then, the samples were sintered at 900 and 1000°C for 15 min in a hydrogen atmosphere, and the fracture surfaces were examined (Fig. 3).

According to the results of metallographic analysis, non-plated fibres practically do not interact with the iron matrix, in contrast to the Ni-plated ones. The contact interaction between the plated fibres and the iron matrix is provided by the Ni coating, which provides better adhesive interaction between carbon fibres and the iron matrix. High adhesive interaction between the components is the necessary condition for the formation of composites with high mechanical properties. To confirm this, the sintered samples were compression tested (see Table 2), and then, the fracture surfaces were examined.

The results of mechanical tests showed that plating fibres with nickel increased both the strength and the plasticity of the materials. After sintering at 900°C, the strength increased by ≅ 5% (from 661 to 697 MPa), whereas relative strain doubled (from 22.7% to 45.1%) (see Table 2). The increase in plasticity is explained by the mechanism of interaction between the fibres and the matrix; the increased contact area of plated fibres provides higher values of yield strength and relative strain. The fractographic studies confirmed ductile nature of fracture (Fig. 4). Elongated fracture dimples are observed, which formed under the action of tangential



a *b*

Fig. 3. Fracture surfaces of the composite materials reinforced with non-plated (*a*) and Ni-plated (*b*) carbon fibres after sintering at 900°C.

TABLE 2. Mechanical properties of different materials.

Material	T, °C	Limit of proportionality $\sigma_{00.1}$, MPa	Proof yield stress $\sigma_{0.2}$, MPa	Maximum stress σ_B, MPa	Relative strain, %
Fe/C/Bakelite (97/0.5/2.5%)	900	103	147	661	22.7
	1000	154	245	1002	23.9
Fe/C + Ni/Bakelite (97/0.5/2.5%)	900	74	182	697	45.1
	1000	198	265	1185	32.4

stresses.

The increase in the sintering temperature to 1000°C led to an increase in the compressive strength up to 1002–1185 MPa, and the specimens with Ni-plated fibres had a strength by 180–185 MPa higher compared to the specimens with non-plated fibres. The significant increase in strength of the composites with Ni-plated fibres can also be attributed to the fact that the nickel coating provides the integrity of the carbon fibres, *i.e.*, the coating acts as a barrier

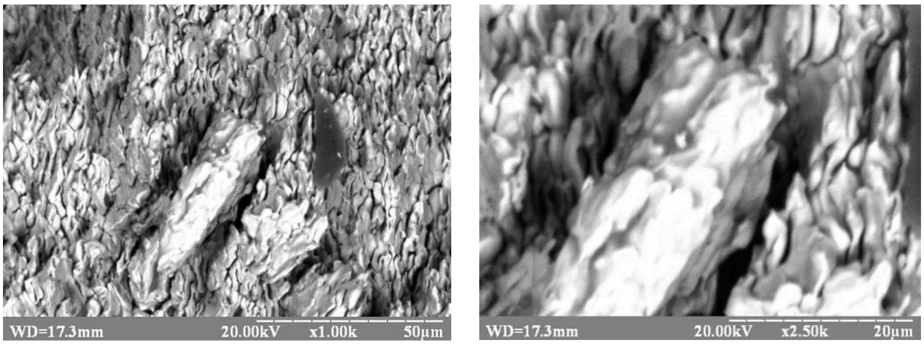


Fig. 4. Fracture surfaces of composites reinforced by Ni-plated carbon fibres (compression tests).

layer and preserves the fibres during pressing and other types of deformation.

3. CONCLUSIONS

The process of plating of carbon fibres with Ni was studied, and the optimal technological parameters of plating were determined: $T = 82–88°C$, and solution with $pH \geq 11$. These parameters provided Ni deposition rate of 2–3 μm/h.

The structure of composites based on an iron matrix with reinforcing carbon fibres was studied. As shown, the interaction between the Ni-plated fibres and the iron matrix is provided by a layer of nickel coating that heightens the adhesion between the carbon fibres and iron.

The results of mechanical tests showed that plating the fibres with Ni provides increasing both maximum strength (by 180–185 MPa) and plasticity of the materials. The increase in plasticity is explained by the mechanism of interaction between the fibres and the matrix: higher contact area of Ni-plated fibres provides higher values of yield stress and relative strain. Another cause of strength increase in iron specimens with Ni-plated fibres is related to the fact that Ni coating provides the integrity of carbon fibres, *i.e.*, the coating acts as a barrier layer and preserves carbon fibres.

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